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ENERGY AND ECONOMIC TRADE OFFS FOR ADVANCED TECHNOLOGY SUBSONIC AIRCRAFT

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It is concluded that wing aspect ratios of future aircraft are likely to significantly increase as a result of new technology and the push of higher fuel prices. Whereas current airplanes have been designed for AR = 7, supercritical technology and much higher fuel prices will drive aspect ratio to the AR = 9-10 range. Composite materials may raise aspect ratio to about 11-12 and practical laminar flow control systems may further increase aspect ratio to 14 or more. Advanced technology provides significant reductions in aircraft take-off gross weight, energy consumption, and direct operating cost.

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Summary

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It is concluded that wing aspect ratios of future aircraft are likely to significantly increase as a result of new technology and the push of higher fuel prices. Whereas current airplanes have been designed for AR = 7, supercritical technology and much higher fuel prices will drive aspect ratio to the AR = 9-10 range. Composite materials may raise aspect ratio to about 11-12 and practical laminar flow-control systems may further increase aspect ratio to 14 or more. Advanced technology provides significant reductions in aircraft take-off gross weight, energy consumption, and direct operating cost.

Introduction

In January 1973, U.S. airlines paid about 12 cents per gallon for their fuel. By October of 1975, U.S. domestic airlines were paying almost 30 cents per gallon and U.S. international airlines were paying about 37 cents per gallon (Fig. 1). By the end of 1976, OPEC crude oil price increases and gradual removal of domestic price controls suggest that fuel prices may rise again. Increases in fuel price such as those experienced over the past few years mean that significant improvement must occur in the energy performance of future aircraft. The impact on the design of aircraft will be great.[1-8] This paper presents an overview of what the development of new technologies such as laminar-flow control (LFC), composite materials, and new airfoils may mean to future aircraft design.

Studies were accomplished by the development of a computer program capable of sizing aircraft for minimum fuel consumption. With this tool, it is possible to take a broad look at technologies and parameters which influence aircraft weight, fuel usage, and other operating cost components. The assumptions on which the program is based limit its use to defining broad effects of aircraft design rather than conducting detailed point designs. Experience to date indicates that this program can be quite useful in making broad assessments of the value of new aircraft technology.

Symbols

AR	Aspect ratio
c	Section chord, ft
C_D	Total drag coefficient
C_{D_i}	Induced drag coefficient
C_{D_o}	Friction drag coefficient
C_L	Cruise lift coefficient
COMP	Composite material
DOC	Direct operating cost, cents per seat statute mile
ENERGY	Energy use, Btu's per seat mile
e = 0.8	Span efficiency factor
L/D	Lift-to-drag ratio
LFC	Laminar-flow control used on wing and tail
M	Mach number
OEW	Operating empty weight, lb
PAX	Number of passengers
R	Range, n. mi.
ROI	Return on investment, percent
S_{wing}	Wing area, ft^2
t/c	Average thickness ratio, percent
$(t/c)_{M_D}$	Average thickness ratio consistent with drag divergence Mach number
TOGW	Take-off gross weight, lb
TURB	Turbulent flow
UW	Unit weight, lb per ft^2 (laminarized wetted area)
Wwing	Wing weight, lb
α	Angle of attack, radians
Λ	Wing sweep angle, degrees
λ = 0.27	Wing taper ratio

Description of Minimum Energy Aircraft Program

Appendix A summarizes the important equations used in the development of the program. Program logic is shown in Figure 2. Passenger number, range, and Mach number are specified. An initial fuel weight and take-off gross weight (TOGW) is assumed. The fuselage is sized to accommodate the payload. Empirical equations (Appendix A) are used to weigh major aircraft components such as the wing and fuselage (with appropriate modifications for high-aspect ratio and advanced technology). A first guess of wing area is made and first-order (no wing-body interference effects) aerodynamics[9] used to calculate cruise performance at $(L/D)_{max}$. Engine size is then determined by weighing cruise thrust requirements against the thrust requirements imposed by a 10,500-foot runway. A climb performance routine is calculated[10] and the engine resized, if necessary, to achieve adequate climb performance. The calculations are then iterated until a convergence is reached which defines the aircraft and its performance for the selected wing area. Wing area is then varied in a search for the aircraft with maximum range,

given the assumed fuel load. The optimum energy airplane to meet the required range is then found by repeating the wing area search for different assumed fuel weights. This part of the program, which defines the optimum energy airplane, provides inputs for the next section of the program to calculate airplane economics.

Economic results are expressed in terms of Direct Operating Costs (DOC), Indirect Operating Costs (IOC), and Return on Investment (ROI). DOC calculations are based on the Air Transport Association model[11] updated to 1975 cost experience.* Indirect Operating Costs are based on a Lockheed Aircraft Corporation model.[12] The ROI calculations utilize discounted cash flow methodology. Baseline fuel price is 30 cents per gallon.

Off-design performance (block fuel and DOC) is then calculated by assuming a full payload and design fuel load for stage lengths less than design range. Approximately 40 seconds of run time on the CDC 6600 computer are needed to define an optimum airplane and determine its economic and off-design performance.

Major assumptions made in developing the program are listed in Figure 3. Table 1 compares a representative trijet configuration[13] with results predicted by the program for a minimum fuel consumption aircraft. Weights, geometry, and mission performance data are given. Even though many parameters, other than fuel consumption, were considered in the trijet design (for example, economic performance), the comparison indicates that realistic aircraft characteristics evolve from the program.

Results

Baseline Airplane

A 200-passenger airplane with 10,000 pounds of cargo load flying at $M = 0.8$ was chosen as a baseline. Additional characteristics of this airplane are given in Table 2, which also includes the baseline characteristics of the laminar-flow control (LFC) configuration. Design parameters studied with the baseline airplane include thickness ratio, aspect ratio, and range. Studies of new technology airplanes are also referenced to this baseline. A high bypass ratio engine is assumed with technology level held constant; the technology level is about that of a JT-9D engine.

Airfoil Model

The baseline configuration was used to study the effects of thickness ratio at various aspect ratios and R = 3000 n. mi. TOGW, ENERGY, and DOC results are given in Figure 4. Use of a constant wing thickness ratio yields a continuous decrease in energy requirements as aspect ratio is increased; however, trends in TOGW and DOC with aspect ratio (AR) are strongly dependent on the assumed thickness ratio.

Minimum energy aircraft with thick wings have their minimum TOGW at higher aspect ratios than do aircraft with thin wings. Thick wing aircraft also have lower TOGW, as would be expected from inspection of the wing weight equation used (see Appendix A) which shows decreasing wing weight with increasing thickness ratio. However, these constant thickness ratio results are misleading. For example, the decrease in DOC that occurs with increasing aspect ratio for $t/c \geq 12$ may be erroneous since these airfoils may not be able to meet a drag divergence criterion. A bad estimate as to the absolute level of average thickness ratio could also lead to significant error.

For these reasons, Reference 14 was used to determine the variation of average wing thickness ratio, $(t/c)_{M_D}$, consistent with a drag divergence Mach number and required wing lift coefficient. It is important to realize that this relationship does not necessarily represent an attainable supercritical technology for the airfoil section, but only serves as a model for the relationship between wing thickness, wing lift coefficient, and Mach number. With this criterion, the wing thickness ratio compatible with drag divergence Mach number (i.e., a 20-count drag rise) varies from 14.1% to 7.8% over the AR range (see $(t/c)_{M_D}$ curve in Fig. 4). The result is an increase in wing weight (at high aspect ratios) which is above and beyond the $(AR)^{1.5}$ penalty (see wing weight equation in Appendix A). Consequently, at high aspect ratios, large penalties occur in TOGW and DOC (Fig. 4).

In addition, at high aspect ratios, the varying thickness ratio compounded the problem of getting enough fuel in the wing; for these aircraft, adequate fuel storage volume in the wing could present a design problem above AR = 10.

Turbulent Airplane Studies

Design Range. The effect of design range on the baseline aircraft is given in Figure 5 for aspect ratios of 7 and 14. As range increases, the extra fuel required to meet mission requirements combines with increases in structural weight to raise take-off gross weight. At AR = 7, which is typical of current commercial transports, energy requirements increase continuously with range; high AR aircraft (AR = 14) show a minimum energy consumption at a design range of about 2200 n. mi. Relative to the AR = 7 aircraft, energy saved with an AR = 14 design is greatest at long range. Best economic performance occurs at ranges between 2000 n. mi. and 3000 n. mi. with best economics at a somewhat higher range for the highest AR. Severe penalties are encountered with long-range capability (>5500 n. mi.) in terms of both energy use and DOC.

Aspect Ratio. The effect of aspect ratio is shown in Figure 6 for ranges of 1000, 3000, and 5000 n. mi. Effects of increased aspect ratio result from a trade of improved aerodynamic efficiency for added structural wing weight (see Appendix A). Up to AR of about 12, this trade is favorable at all ranges in the sense that energy requirements are reduced. At a range of 1000 n. mi., however, the resulting TOGW increases with increasing AR. At 5000 n. mi. range, the fuel saved with increased AR more than offset the structural weight penalty and TOGW decreases when AR is increased from 7 to 10. Above AR of about 12, the trade is not favorable and TOGW and fuel usage begin to increase with AR. Lowest DOC's are obtained at aspect ratios between 9 and 10. These optimum DOC's occur at a higher aspect ratio than today's AR ≈ 7 designs because of the sharp fuel price increases which have occurred during the past 2-1/2 years (the present study uses a fuel price of 30 cents per gallon compared to an earlier 12 cents per gallon) and the existence of supercritical airfoil technology. For the three ranges shown, the lowest DOC's occur with R = 3000 n. mi. for all aspect ratios. DOC increases rapidly when AR > 11 because of the extra fuel and purchase price increase resulting from the much increased structural weight.

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*APPENDIX B.

Laminar-Flow Control

Controlling the boundary layer to maintain laminar flow on an airplane can offer large benefits. Laminar-Flow Control (LFC) results in much lower friction drag and therefore reduced fuel use. Figure 7 illustrates the concept of using suction to stabilize the initial laminar boundary layer such that laminar flow can be maintained far beyond the length normally observed for transition to turbulent flow. Suction power requirements are small compared to the reductions obtained in propulsive power. Much significant work in LFC using the suction concept was accomplished with the X-21 flight tests made between 1962-1965.[15-19] This work showed that LFC could, in fact, be achieved in flight. Remaining uncertainties revolve largely around questions of reliability, maintenance, and cost.

As a result of the national energy crisis, NASA is taking a fresh look at LFC's potential and problems.[20] Two studies by Lockheed[21] and Boeing[22] have recently been completed under NASA sponsorship. Because of the potential for energy conservation with LFC technology, the present study has also looked at some of the major questions which surround the application of LFC to commercial transport aircraft.

LFC Configuration. For comparison to the baseline turbulent airplane, LFC airplanes were studied assuming laminar flow exists over the wing and tail of the aircraft (see Table 3 for a typical configuration comparison). The LFC system is turned on once the aircraft reaches cruise altitude. The propulsion system was sized to include the power required to run the LFC system pumps.

Figure 8 shows the effect of LFC with range. LFC benefits in reduced weight, energy, and direct operating cost grow rapidly as range increases because of the greater importance of aerodynamic efficiency at long range. LFC also increases the range at which minimum DOC occurs. The effect of AR for aircraft designed for LFC relative to the turbulent baseline at R = 3000 n. mi. is shown in Figure 9. LFC delays the TOGW increase which occurs at AR = 10 with the turbulent airplanes. In addition, the weight penalty paid with the turbulent airplane at AR = 14 is greatly reduced with LFC. LFC aircraft energy requirements continually decrease as AR increases from 7 to 14, whereas the AR = 14 turbulent airplane shows increased energy requirements relative to lower aspect ratios. LFC reduced direct operating costs at all aspect ratios studied. Even the DOC penalty from an AR = 14 configuration is largely eliminated with LFC. These favorable results using LFC occur despite built-in economic penalties equal to 17% higher maintenance and 3% higher purchase price assumed for the LFC airplane (Table 3), based on the results of Reference 21.

LFC wings have lower lift coefficients and hence greater thickness ratios than their turbulent counterparts (Fig. 10). This follows since at $(L/D)_{max}$, $C_L = \sqrt{\pi \, AR \, C_{D_o} \, e}$; since LFC reduces C_{D_o}, C_L is also reduced and the wing can have a larger thickness ratio for the same drag divergence Mach number. As aspect ratio increased, wing thickness ratio for the optimum turbulent configuration decreased (Fig. 10), and fuel volume efficiency decreased. For turbulent airplanes with $AR \geq 10$, not enough wing volume was available to store the fuel needed for long-range missions. Turbulent airplanes of high aspect ratio and low passenger capacity may therefore require wing pod tanks[21] or fuel storage in the fuselage. In contrast, no fuel volume problems were encountered with the AR = 14, R = 3000 n. mi., LFC configuration. LFC airplanes, therefore, may offer this potential design simplification although LFC ducting volume requirements present an added problem. Wing box volume was estimated assuming a spar separation distance of one-half the chord length, and fuel volume was taken as 70% of the wing box volume.

The effect of LFC system unit weight (UW in lb per sq ft of laminarized area) is given in Figure 11 for varying AR and R = 3000 n. mi. Baseline unit weight (1.26 from Ref. 21) was varied from 2.52 to 0.63 (not shown). Relative to the baseline, UW = 0.63 provided only minor reductions in TOGW, whereas UW = 2.52 wipes out much (but not all) of the TOGW savings possible at low AR with LFC. Energy consumption is relatively unaffected by unit weight changes and large energy savings result even if UW = 2.52. In contrast to the turbulent configuration, the UW = 2.52 airplane used less energy at AR = 14 than at lower aspect ratios. Economic performance is best at UW = 1.26, but even the UW = 2.52 airplane has a lower DOC than the turbulent baseline. Further work on LFC designs may enable the unit weight penalty to be reduced below 1.26, as design techniques are developed which use the LFC suction surfaces and ducting to help carry structural loads.[22]

Composites

Figures 12 and 13 show the benefit which composite materials will have on the baseline turbulent and LFC configurations. Estimates of wing, tail, fuselage, and landing-gear weight resulting from application of composite material were obtained from Reference 23 (see Table 4). It is thought that this degree of composite application (≈40%) might be applied to an airplane introduced in 1985. Significant reductions in TOGW, energy, and DOC occur with introduction of composite material. Figure 12 shows that at R = 3000 n. mi., composites have a bigger effect on TOGW than does LFC; however, LFC saves more energy and has better economic performance than does composites. At R = 5000 n. mi., LFC reduces both TOGW and energy to a greater extent than does composites (Fig. 12). With varying aspect ratio (Fig. 13) and R = 3000 n. mi., an LFC airplane made of composite materials eliminates the TOGW and DOC penalty paid for the AR = 14 design (relative to AR = 11). These calculations must be viewed with caution, however, since wing weights are estimated using a correlation of historical data based on aluminum aircraft and then corrected to expected composite material weight. Best economic performance is obtained with an LFC airplane built of advanced materials. The price of composite airplanes is found by calculating price as if an aluminum airplane were being costed, and then adding 10% to this value; the resulting composite airplane price is typically about 1%-5% under the price of an equivalent aluminum airplane. Maintenance characteristics are assumed equivalent to that of aluminum airplanes based on the encouraging (but limited) data obtained to date through in-service flight tests made with composite materials on secondary structures. Since energy use is decreasing even at AR = 14, other advanced technology (which lowers structural weight) beyond that discussed in this paper may eventually lead to practical configurations with aspect ratios above 14. Examples of such technologies include more advanced airfoils, greater composite application, laminarized strut-braced wings of very high AR, and active control systems.

Advanced Airfoils

The effect of advanced airfoil technology is illustrated in Figure 14. The advanced configuration represents airfoils with drag divergence Mach numbers 0.025

and 0.05 greater than that attained by supercritical airfoils in Reference 14. Admittedly, attainment of the benefits represented by these cases is a difficult goal to reach if, in fact, reachable. The impact of such an airfoil is relatively small at low aspect ratios. However, the TOGW, energy, and DOC benefits are sizable at high aspect ratios.

These results have an interesting implication for LFC aircraft. Laminar-flow control thins the airfoil boundary layer and thus permits a thicker, lighter-weight wing to be used (without a drag penalty). Therefore, LFC will provide an additional synergistic benefit perhaps comparable to that shown in Figure 14 for the 0.025 Mach number increase. No benefit was taken for this effect in the LFC calculations made in this paper.

In addition, high-aspect-ratio airplanes (turbulent or laminar) require cruise lift coefficients that will be difficult to achieve even with advanced airfoil technology. LFC, with lower required lift coefficients, alleviates this problem (Fig. 10).

Economics

Turbulent Configuration. The effect of aspect ratio on DOC for various fuel prices and ranges is shown in Figure 15. Clearly, if fuel prices continue to rise relative to other costs, higher AR will be economically desirable for future aircraft. At all ranges, the effect of increasing fuel price is to increase the aspect ratio at which minimum DOC occurs. Also, at a constant fuel price, increasing the design range increases the need for improved aerodynamics and, therefore, increases the AR at which minimum DOC occurs. Dramatic changes in airplane design can occur as a result of the interaction of these parameters. For example, at R = 1000 n. mi. and 30 cents per gallon fuel, an AR ≈ 8 airplane has the lowest DOC, and DOC varies little between AR = 7-11. In contrast, at R = 5000 n. mi. and $1.20 per gallon fuel, an AR = 11 airplane clearly has the lowest DOC.

Laminar-Flow Control. The effect of increases in purchase price and maintenance cost for the LFC airplane is shown in Figure 16. With AR = 10 and 30 cents per gallon fuel, the LFC airplane must cost 11% more than expected (or have an 18% higher maintenance cost) for the airplane's DOC to be equal to the turbulent airplane's DOC. If fuel costs 60 cents per gallon, it would take either a 37% increase in purchase price or a 50% increase in maintenance cost to wipe out the LFC benefits. At AR = 14, LFC cost increases must be even greater to eliminate the anticipated savings. It is evident that the payoff from LFC is large enough to overshadow possible maintenance and purchase price increases.

The relative contribution which different costs make to DOC is given in Table 5 for turbulent and LFC airplanes at fuel prices of 30 cents and 60 cents per gallon. As aspect ratio increases, fuel cost becomes less important and purchase price becomes more significant. Laminar-flow control significantly reduces the importance of fuel costs to DOC. In every case listed in Table 5, except two, fuel cost is seen to be the major element of DOC. Therefore, technology which reduces fuel cost is likely to be more important in the future than in the past.

Conclusions

A broad look was taken at how changes in future aircraft design and technology might impact commercial aircraft trade offs between TOGW, energy use, and DOC. Subject to the ground rules and assumptions on which the study was based, the following conclusions were reached:

Turbulent Airplanes. Energy use per passenger mile is lowest at $R \leq 3000$ n. mi. Best DOC's are obtained between ranges of 2000 n. mi. and 3000 n. mi. at all aspect ratios. Severe penalties occur at long range (R ≈ 5000 n. mi.) in terms of both energy use and direct operating cost. High aspect ratio, long-range (AR ≈ 10, R = 5000 n. mi.) aircraft can conceivably show lower TOGW than AR = 7 aircraft.

Laminar-Flow Control. LFC systems provide significant energy savings when applied to current AR = 7 aircraft. TOGW, energy, and DOC savings increase dramatically with design range. LFC will be of even more value to the high aspect ratio (AR = 10-14) aircraft of the future because the greater aerodynamic efficiency realized with LFC systems reduce the total drag and, consequently, negate further the weight penalties that must be paid for high-aspect-ratio design. Successful application of LFC systems, therefore, will tend to increase the aspect ratios of future airplanes. Aircraft energy requirements for LFC configurations continually decreased as AR was increased from 7 to 14 in contrast to the turbulent airplane results. LFC benefits are greatest at high range and high aspect ratio. Unit weight (lb/ft^2) of the LFC system has a small effect on energy saved but increased LFC unit weight penalties are more significant in TOGW and DOC results.

Composites. Significant reductions in TOGW, energy, and DOC occur with introduction of composite material. At R = 3000 n. mi., composites had a larger effect on TOGW than did LFC, although LFC saved more energy and had a lower DOC than did composites. Also, at R = 3000 n. mi., an LFC composite airplane nearly eliminated the TOGW and DOC penalty paid for an AR = 14 design. Best economic performance was obtained with an LFC airplane built of advanced materials.

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Appendix A. Main Equations Used in Minimum Energy Aircraft Program

Aerodynamics

$$C_L = \left(\frac{dC_L}{d\alpha}\right)\alpha \; ; \; \frac{dC_L}{d\alpha}^{*} = \frac{2\pi}{\sqrt{1 - M^2}} (\cos \Lambda) \left\{\frac{F}{2 + F\sqrt{1 + 4/F^2}}\right\} \quad \text{where} \quad F = \frac{AR\sqrt{1 - M^2}}{\cos \Lambda}$$

$$C_{D_i} = \frac{C_L^{\,2}}{\pi e AR} \; ; \quad (L/D)_{max} = 0.5\sqrt{(\pi AR e)/C_{D_o}}$$

$$(C_L)_{(L/D)_{max}} = \sqrt{\pi AR e C_{D_o}}$$

$C_{D_o} = K \sum C_F$ (wetted area/wing area) where $K = 1.15$ (correction factor for parasite drag)

C_F - Laminar: Blasius

C_F - Turbulent: Prandtl-Schlichting

Weights

Fuselage weight** = (WOSB) (body area) where $WOSB = 2.6\sqrt{3.75 \times TOGW \times 10^{-6}}$, or

$= 4.75$ minimum (selected minimum gage)

Wing weight*** $= 3534 + ?.847\left[S_{Wing} + 0.3 K_W \left(\frac{TOGW}{S_{Wing}}\right)(S_{Wing})^{1.5} \times 10^{-6}\right]$

$$\text{where} \quad K_W = \frac{3.75 (AR)^{1.5} (KZF)^{0.5} (1 + 2\lambda)}{(t/c)(1 + \lambda)\cos^2 \Lambda} \; ; \; KZF = \frac{\text{Zero fuel weight}}{TOGW}$$

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*Shapiro, p. 422.

**Correlation of historical data by L. Robert Jackson, NASA High-Speed Aerodynamics Division. Design Concepts Group, Langley Research Center.

***Obtained from McDonnell Douglas Corporation, NAS1-13964.

Tail weight = 5.0 (horizontal tail area + vertical tail area)

Engine weight = take-off thrust/3.38

Payload weight = (210) PAX + cargo weight

Fuel weight = cruise fuel + climb fuel + reserve fuel; where reserve fuel = 0.18 (fuel weight)

Fixed weight* = 1.1933 [(S_{Wing} + (1.44) (total tail area)] + 1.98 (gallons of fuel)$^{0.4416}$
(hydraulic systems) (fuel instruments)

+ [40.1 + (7.53 x 10^{-4}) (take-off thrust)] (No. engines) + 330.8 + (0.444) PAX
(propulsion instruments) (remaining instruments)

+ (18.83) (PAX)$^{0.9836}$ + (28.513) PAX$^{0.9087}$ + (34.875) PAX$^{1.1779}$
(electrical) (air conditioning, aux. power & pneumatics) (PAX furnishings & equipment)

+ (0.038) (wing area) + (0.238) (wing area) + 51
(anti-icing group) (anti-icing group) (load and handling group)

LFC system weight = (2) (UW) (laminarized area)

Engine

Bypass ratio = 4.9

Specific fuel consumption at sea level = 0.395 per hour

Specific fuel consumption at cruise = 0.657 per hour

Fan pressure ratio at cruise = 1.56

*Obtained from PRC Systems Sciences Company.

APPENDIX B.- EQUATIONS USED TO CALCULATE DIRECT OPERATING COST - 1975 COEFFICIENTS*

CREW PAY ($/BLOCK HOUR)	
3 MAN JET	$24.261\left(V_c \times \frac{TOGW}{10^5}\right)^{.3} + 57.620$
NON-REVENUE FACTOR	1.02 ON FUEL AND MAINTENANCE
AIRFRAME MAINTENANCE-CYCLE	
MATERIAL ($/CYCLE)	$1.9229\ (Ca/10^6) + 2.2504$
DIRECT LABOR (MH/CYCLE)	$.21256\ [\mathrm{Log}_{10}(Wa/1000)]^{3.7375}$
AIRFRAME MAINTENANCE - FLIGHT HOUR	
MATERIAL ($/FH)	$1.5994\ Ca/10^6 + 3.4263$
DIRECT LABOR (MH/FH)	$4.9169\ [\mathrm{Log}_{10}(Wa/1000)] - 6.425$
ENGINE MAINTENANCE - CYCLE	
MATERIAL ($/CYCLE)	$[3.6698\ (Ce/10^6) + 1.3685]\ Ne$
DIRECT LABOR (MH/CYCLE)	$.20\ Ne$
ENGINE MAINTENANCE - FLIGHT HOUR	
MATERIAL ($/FH)	$[28.2353\ (Ce/10^6) - 6.5176]\ Ne$
DIRECT LABOR (MH/FH)	$[T/10^3/(.82715\ T/10^3 + 13.639)]\ Ne$
BURDEN $/DIRECT MAINTENANCE $	1.00
MAINTENANCE LABOR RATE ($/MANHOUR)	8.60
INSURANCE (% PRICE/YEAR)	1.0
INVESTMENT SPARES RATIO (%)	
AIRFRAME	6
ENGINE	30
DEPRECIATION SCHEDULE (YEARS/RESIDUAL VALUE)	14/0

TOGW - Maximum Takeoff Gross Weight - Lbs.
Ca - Airframe Price - $
Ce - Engine Price - $ (Excluding Reverser)
Ne - Number of Engines
V_c - $715 \times M - 75 \times M^2$ ($M < .9$)

Wa - Airframe Weight - Lbs.
M - Mach No.
FH - Flight Hours
MH - Manhours
T - Sea Level Static Thrust-Lbs.

*Obtained from Boeing Commercial Aircraft Company

TABLE 1. COMPARISON OF REPRESENTATIVE WIDE BODY TRIJET WITH PRESENT STUDY RESULTS

	Trijet	Present study
Weight, lb		
TOGW	555000	533600
Wing	57878	56875
Fuel	187000	183170
Tail	10000	8927
Engine	48856	52019
Body	46275	46738
Empty	349955	352430
Fixed	76288	83910
Payload (inc. cargo)	104573	103960
Number of passengers	376	376
Altitude, ft	31000	37619
Length, ft	182	178
Wing loading, lb per ft^2	152	142
Wing area, ft^2	3647	3774
Span, ft	165	155
Horizontal tail area, ft^2	1336	1080
Vertical tail area, ft^2	605	651
Climb range, n. mi.	193	175
Climb time, minutes	26.4	23.9
Available fuel storage, lb	240000	211000
Take-off thrust, lb	153000	176000
Average t/c, percent	11.2	10.4

TABLE 2. BASELINE TURBULENT/LFC AIRPLANE CHARACTERISTICS

Mach number	0.8
Seats	200
Cargo load, lb	10000
Sweep, deg	25
Aspect ratio	7
Runway length, ft	10500
Reserve fuel, as percent of total fuel	18
Airframe material	Aluminum
Engine technology	[illegible]
Engine number	4
Fuel cost, cents per gallon	30
Passenger weight + baggage, lb	210
LFC components	Wing + tail
Wing and tail area with LFC, percent	100

TABLE 3. COMPARISON OF NOMINAL TURBULENT AIRPLANES TO LFC AIRPLANES
M = 0.8
Range = 3000 n. mi.
PAX = 200
$\Lambda = 25°$

	AR = 7		AR = 14	
	Turbulent	LFC	Turbulent	LFC
TOGW, lb	224070	21343[illegible]	261440	221100
OEW, lb	102530	107788	147540	125090
Wing wt, lb	36641	[illegible]	55511	39482
Body wt, lb	43189	43189	43189	43189
Engine wt, lb	20247	17949	23655	18119
LFC system wt, lb	------	[illegible]020	------	4833
Block fuel, lb	58860	4[illegible]470	52600	37420
Span, ft	109	118	167	164
Length, ft	151	151	151	151
Wing area, ft^2	1708	1992	1999	1918
Cruise altitude, ft	35260	[illegible]	42662	40654
Cruise L/D	15.2	19.8	21.1	26.8
Wing loading, lb per ft^2	131	107	131	115
Airplane price, $\$ \times 10^6$	9.36	9.91	12.37	10.98
DOC	1.085	1.036	1.169	1.036
Relative LFC maintenance, percent	------	17	------	17
Relative LFC purchase price, percent	------	3	------	3
LFC system unit weight, lb per ft^2	------	1.26	------	1.26

TABLE 4. COMPOSITE MATERIAL COMPONENT WEIGHT AS A PERCENT OF CONVENTIONAL WEIGHT

Wing	71.5
Body	78.2
Tail	78.0
Landing gear	86.0

Source: Reference 23

TABLE 5. COST AS A PERCENT OF DIRECT OPERATING COST
Range = 3000 n. mi.

	Turbulent						Laminar					
	30 cents/gal			60 cents/gal			30 cents/gal			60 cents/gal		
	AR			AR			AR			AR		
	7	10	14	7	10	14	7	10	14	7	10	14
Fuel	36.0	32.6	29.8	52.9	49.1	46.0	29.2	26.3	24.0	45.2	41.6	38.7
Maintenance	18.4	19.4	20.6	13.5	14.7	15.9	22.2	23.1	23.9	17.2	18.3	19.3
Crew	25.9	26.7	25.3	19.1	20.1	19.5	26.9	27.7	27.7	20.8	21.9	22.3
Depreciation + insurance	19.7	21.3	24.3	14.5	16.1	18.6	21.7	22.9	24.4	16.8	18.2	19.7

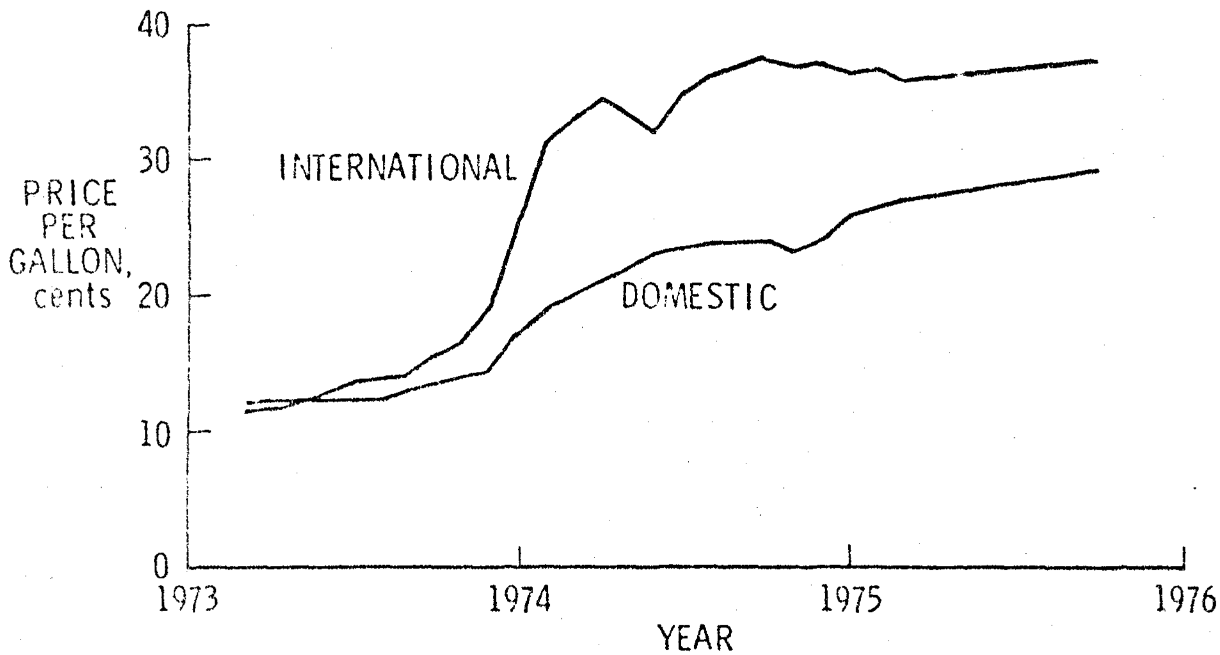

Figure 1. Average U.S. commercial jet fuel price.

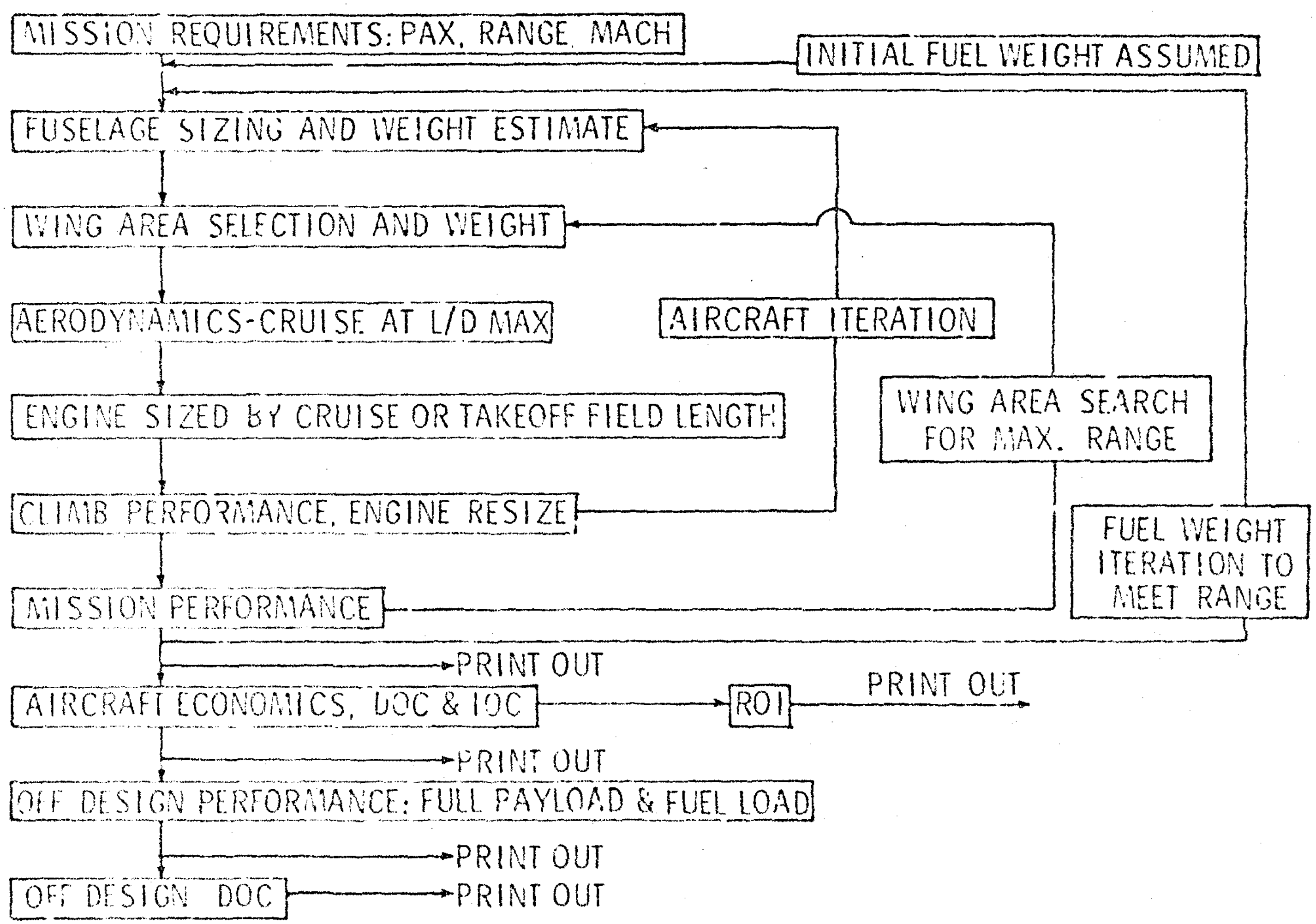

Figure 2. Minimum energy aircraft program logic.

FIRST ORDER AERODYNAMICS

TRIM OR BALANCE NOT CONSIDERED

HISTORICAL PARAMETRIC WEIGHTS - ALUMINUM
- EXTRAPOLATED TO HIGH ASPECT RATIO

WEIGHT REDUCTION FACTORS USED FOR COMPOSITE MATERIALS

EMPENNAGE SIZED BY TAIL VOLUME COEFFICIENTS

HIGH BYPASS RATIO ENGINE MODEL - CONSTANT TECHNOLOGY

Figure 3. Major program assumptions.

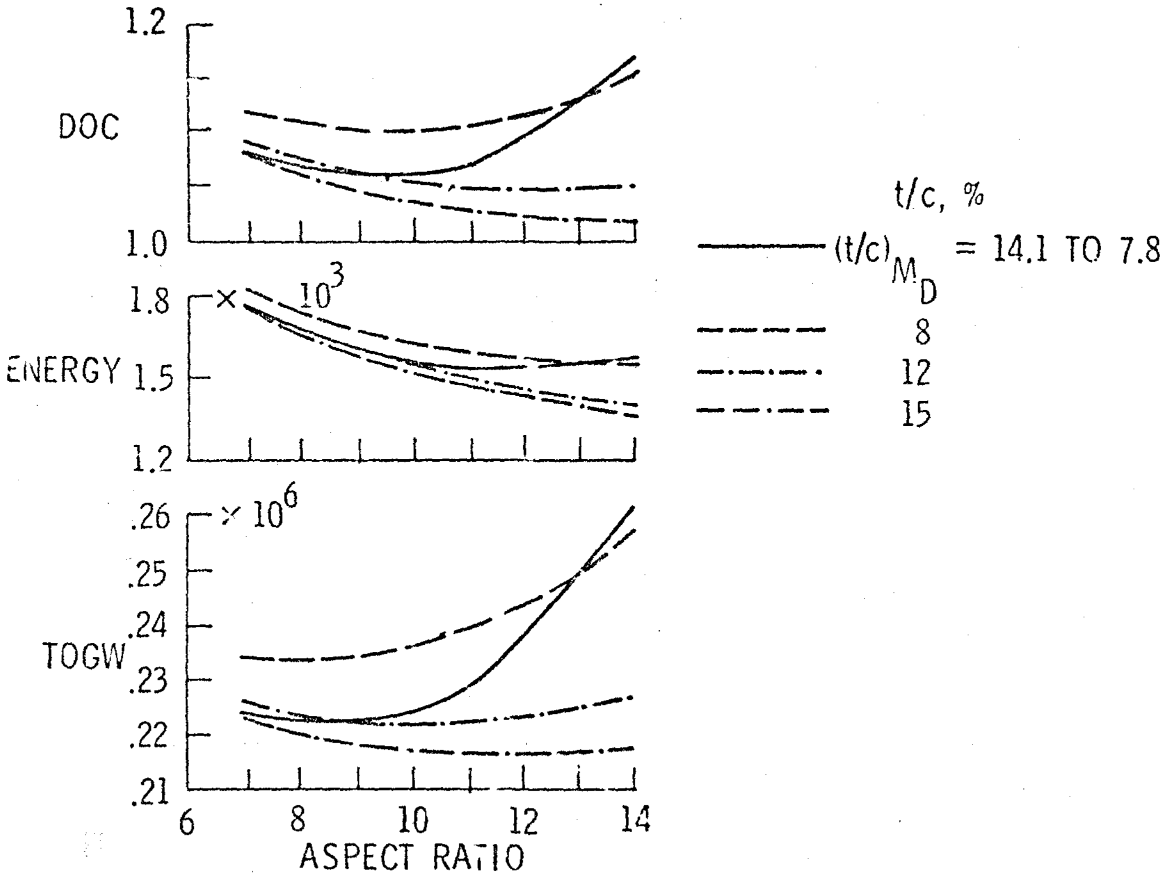

Figure 4. Wing thickness ratio and aspect-ratio effects at R = 3000 n.mi. for turbulent flow aircraft.

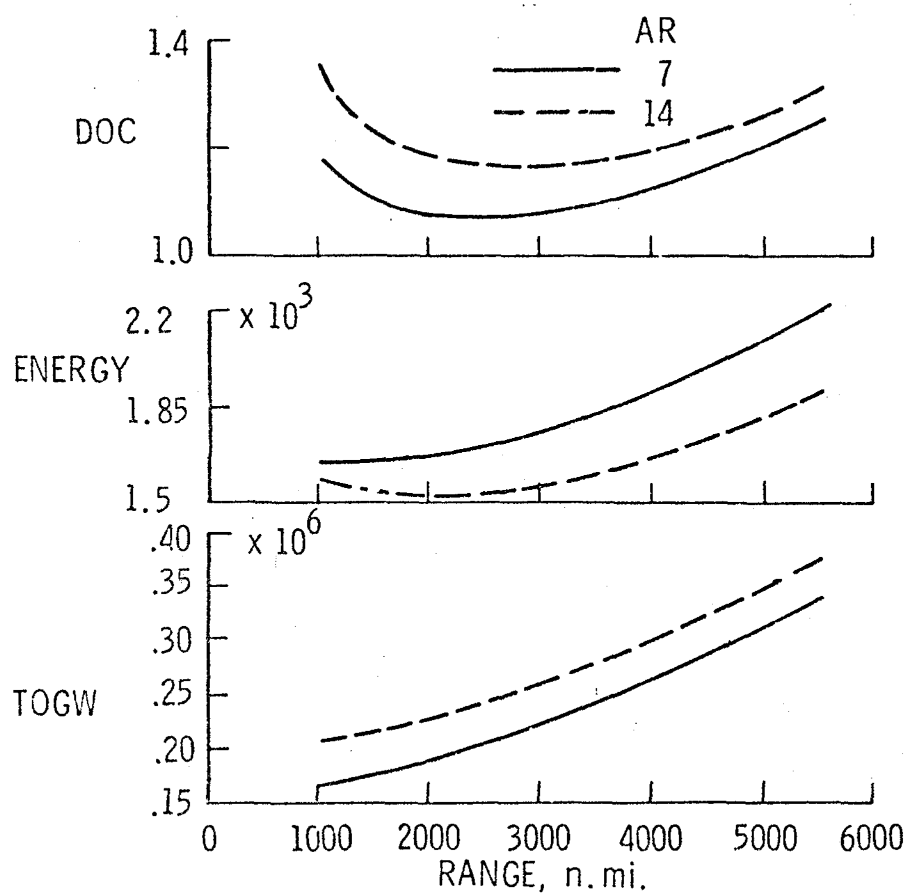

Figure 5. Design range effects for turbulent flow aircraft.

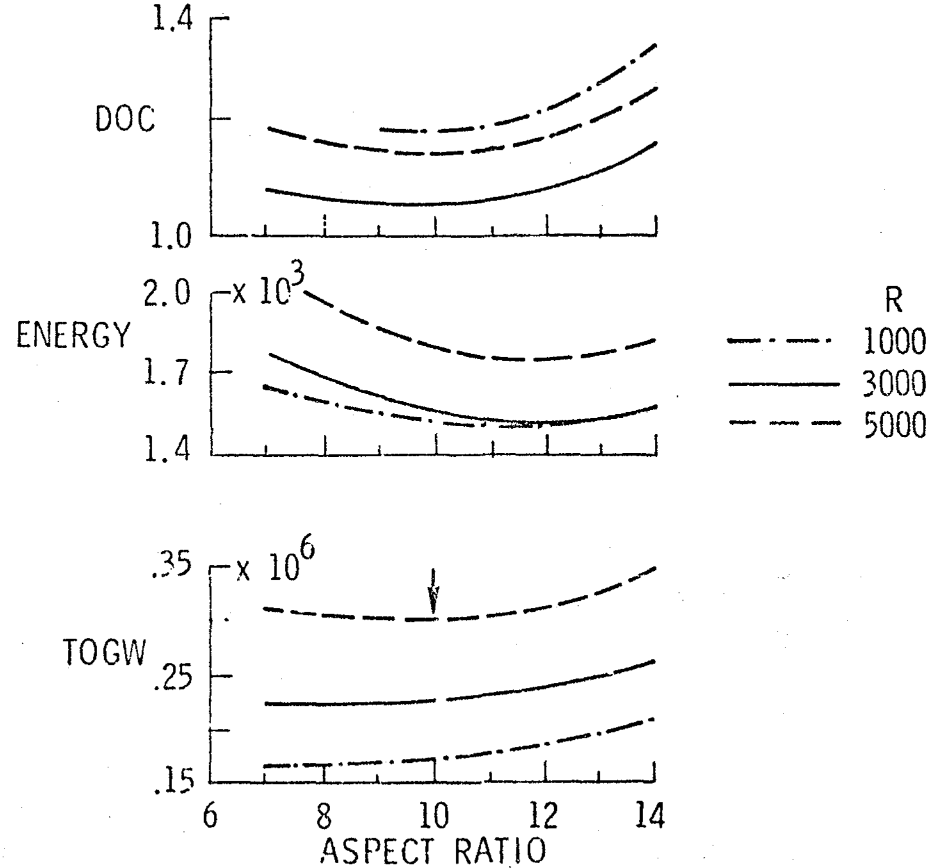

Figure 6. Aspect-ratio effects for turbulent flow aircraft.

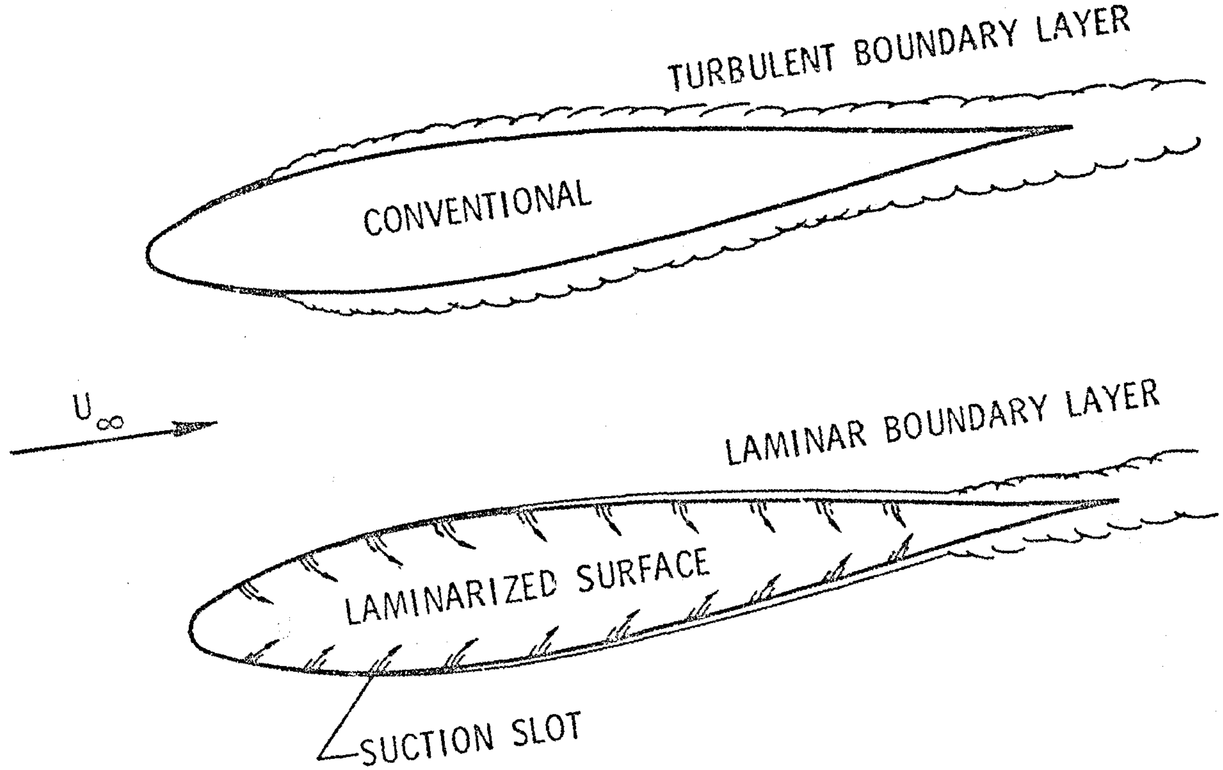

Figure 7. Laminar flow control concept using suction.

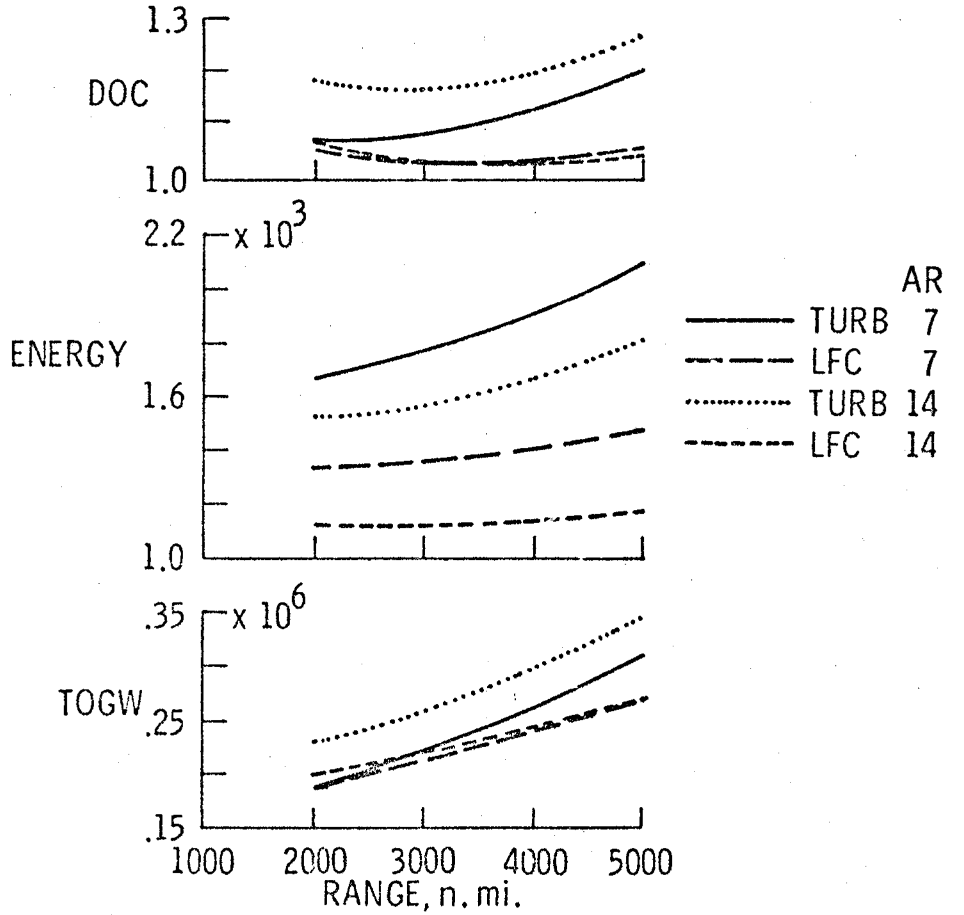

Figure 8. Effect of laminar flow control and range.

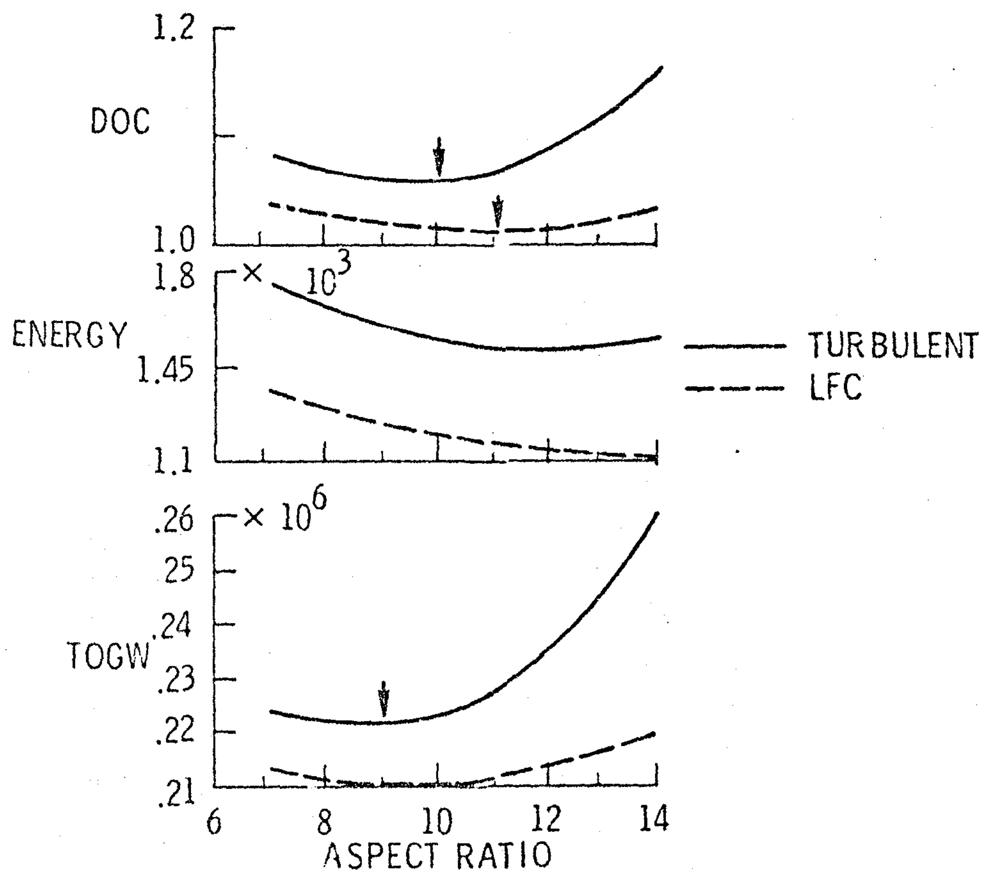

Figure 9. Effect of laminar flow control and aspect ratio at R = 3000 n.mi.

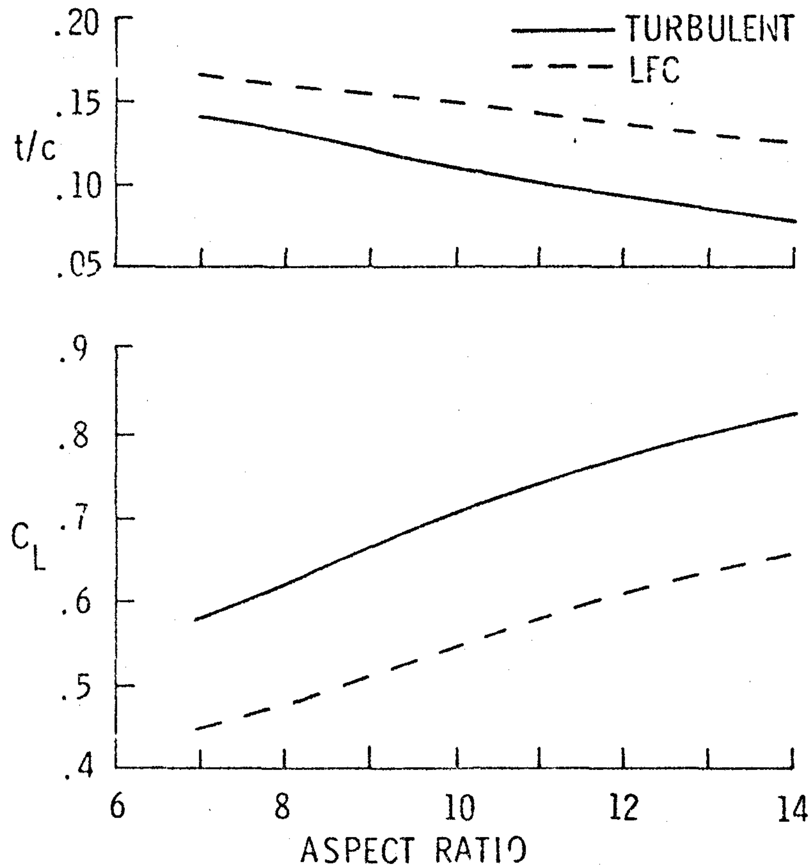

Figure 10. Wing thickness ratio and cruise lift coefficient for LFC aircraft at R = 3000 n.mi.

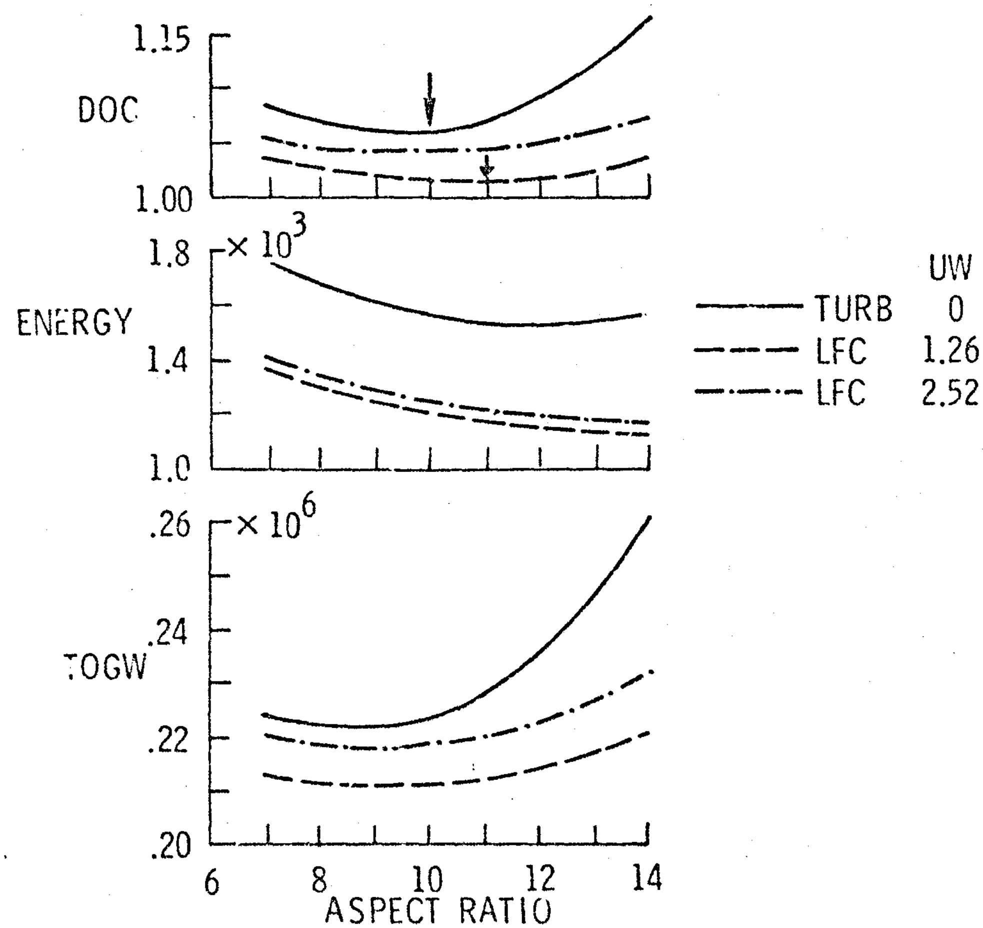

Figure 11. Effect of laminar flow control system unit weight on aluminum aircraft at R = 3000 n.mi.

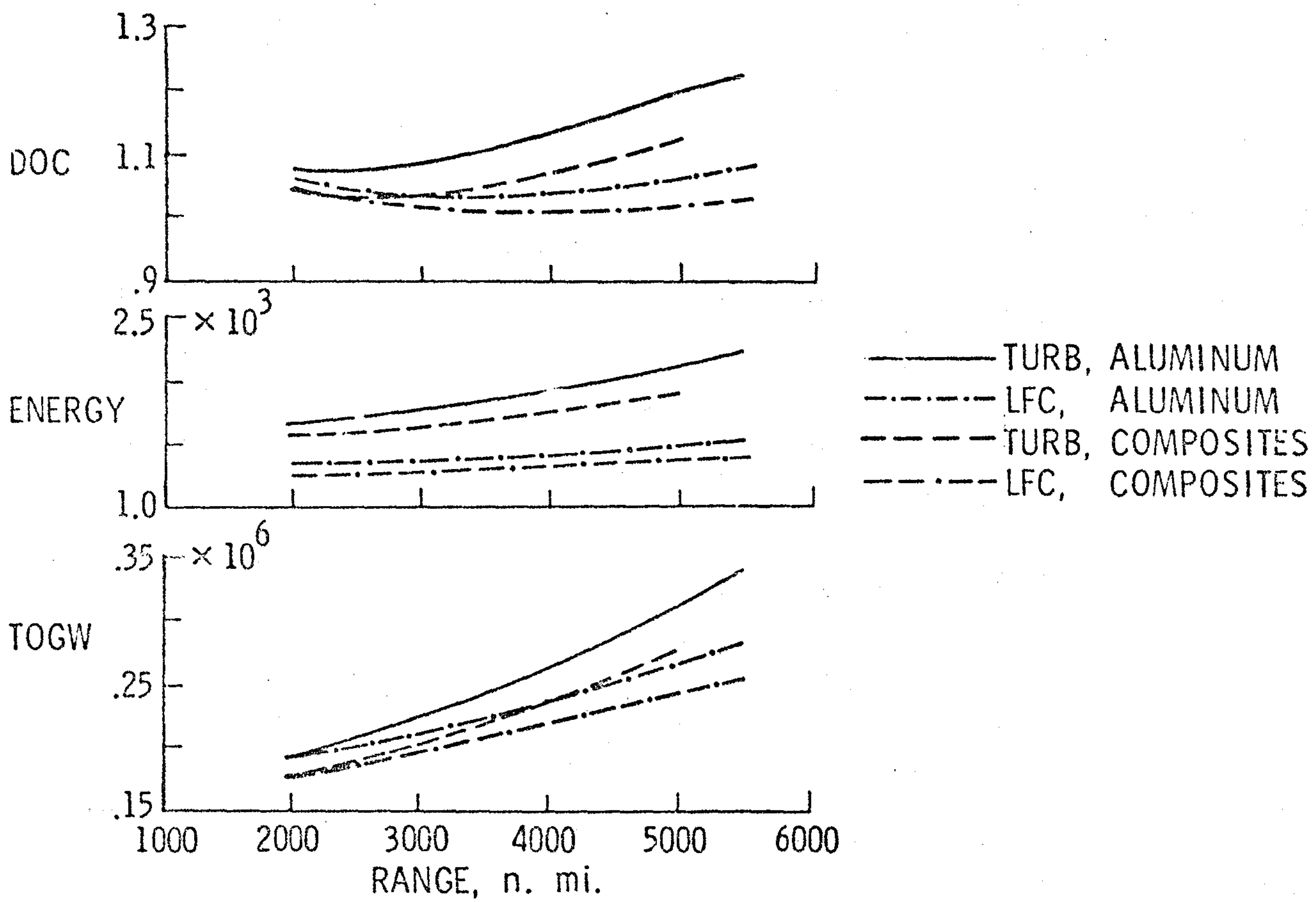

Figure 12. Laminar flow control and composite material effects on aircraft with AR = 7 for various design ranges.

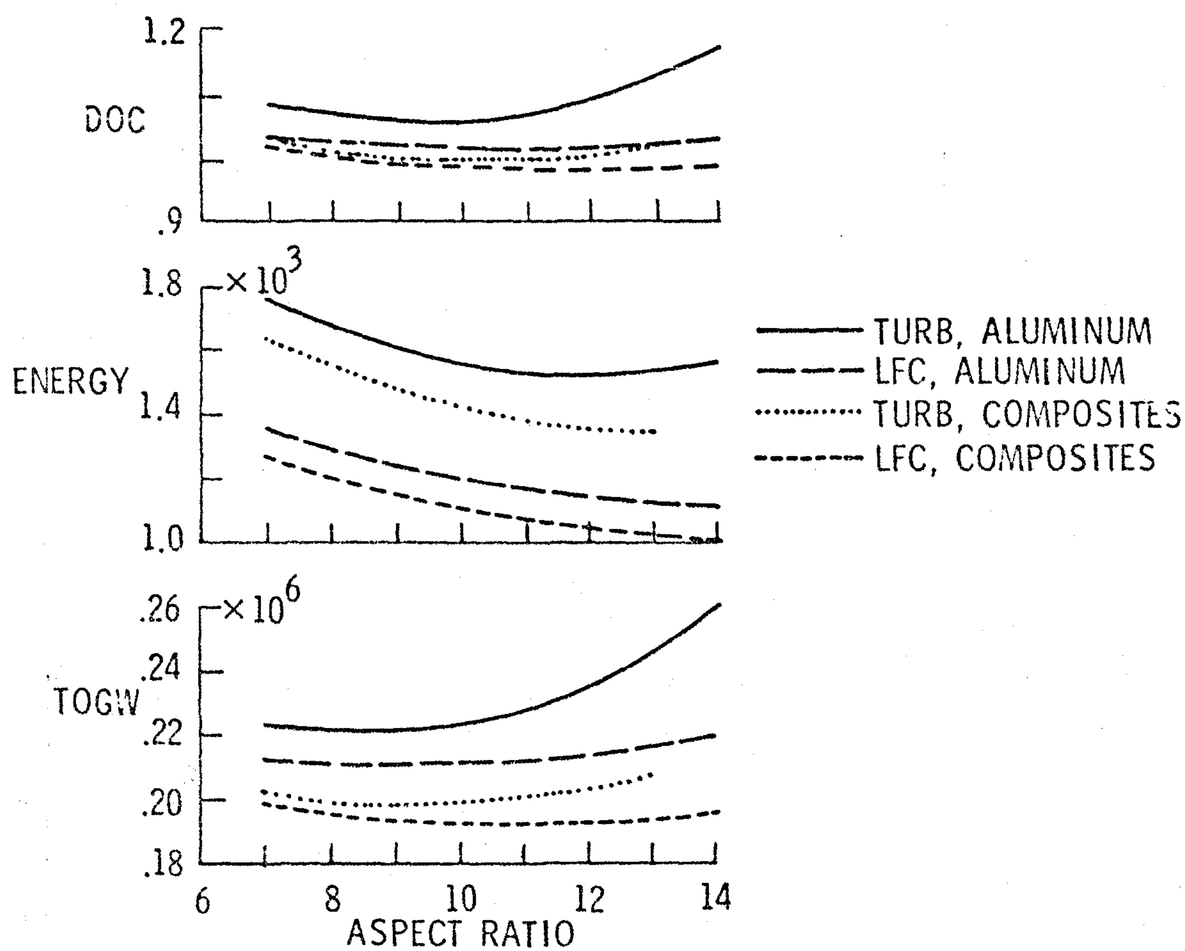

Figure 13. Effects of laminar flow control and composite material on aircraft at R = 3000 n.mi. for various aspect ratios.

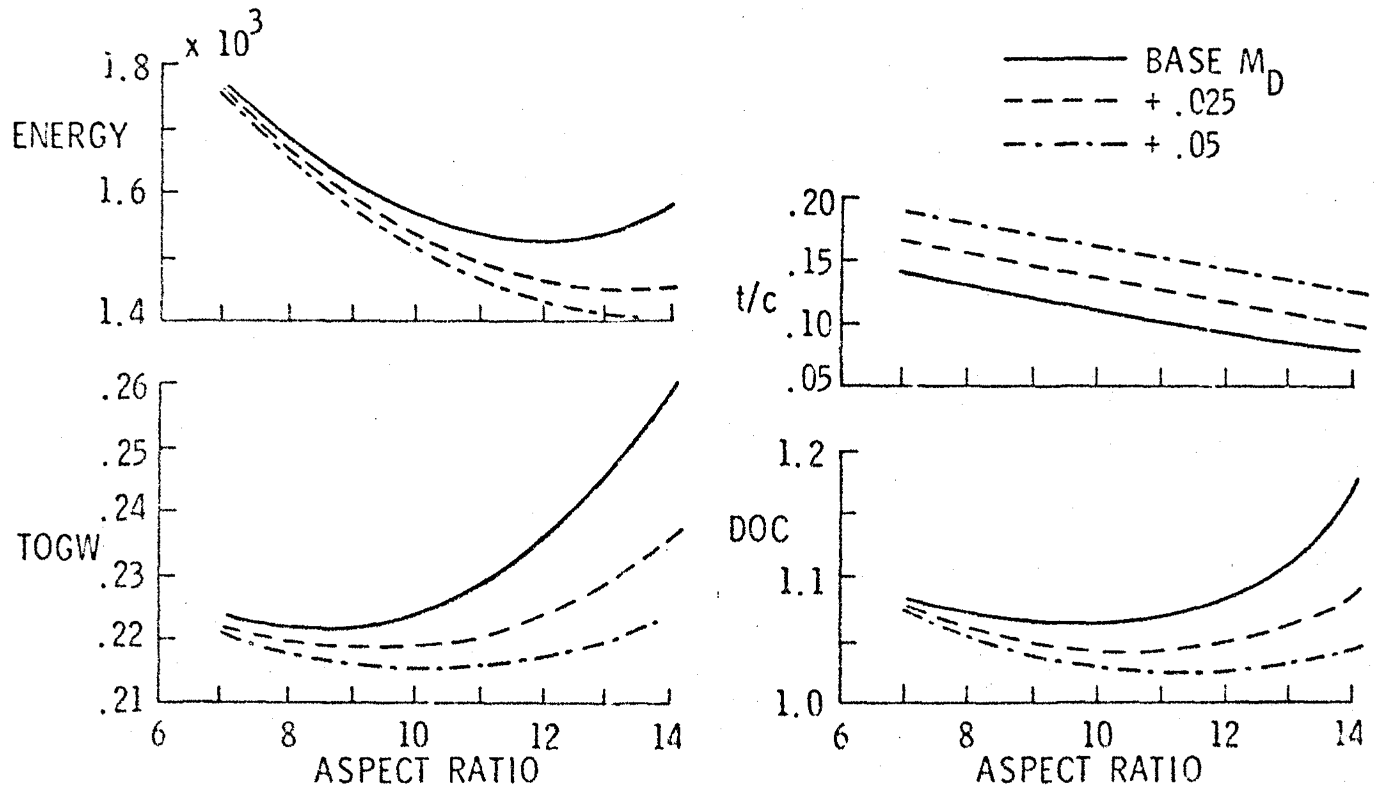

Figure 14. Effect of advanced airfoil technology at R = 3000 n.mi. in turbulent flow.

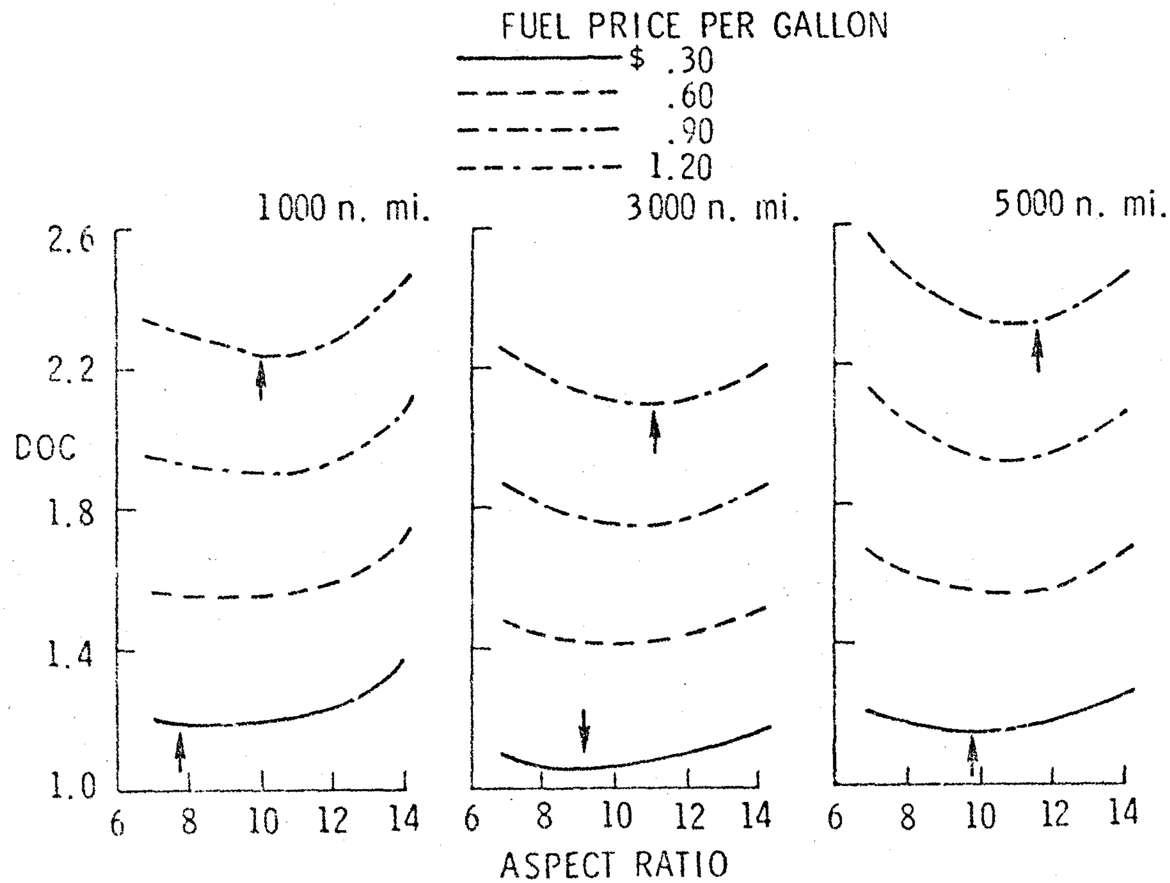

Figure 15. Effect of aspect ratio and fuel price versus minimum DOC in turbulent flow.

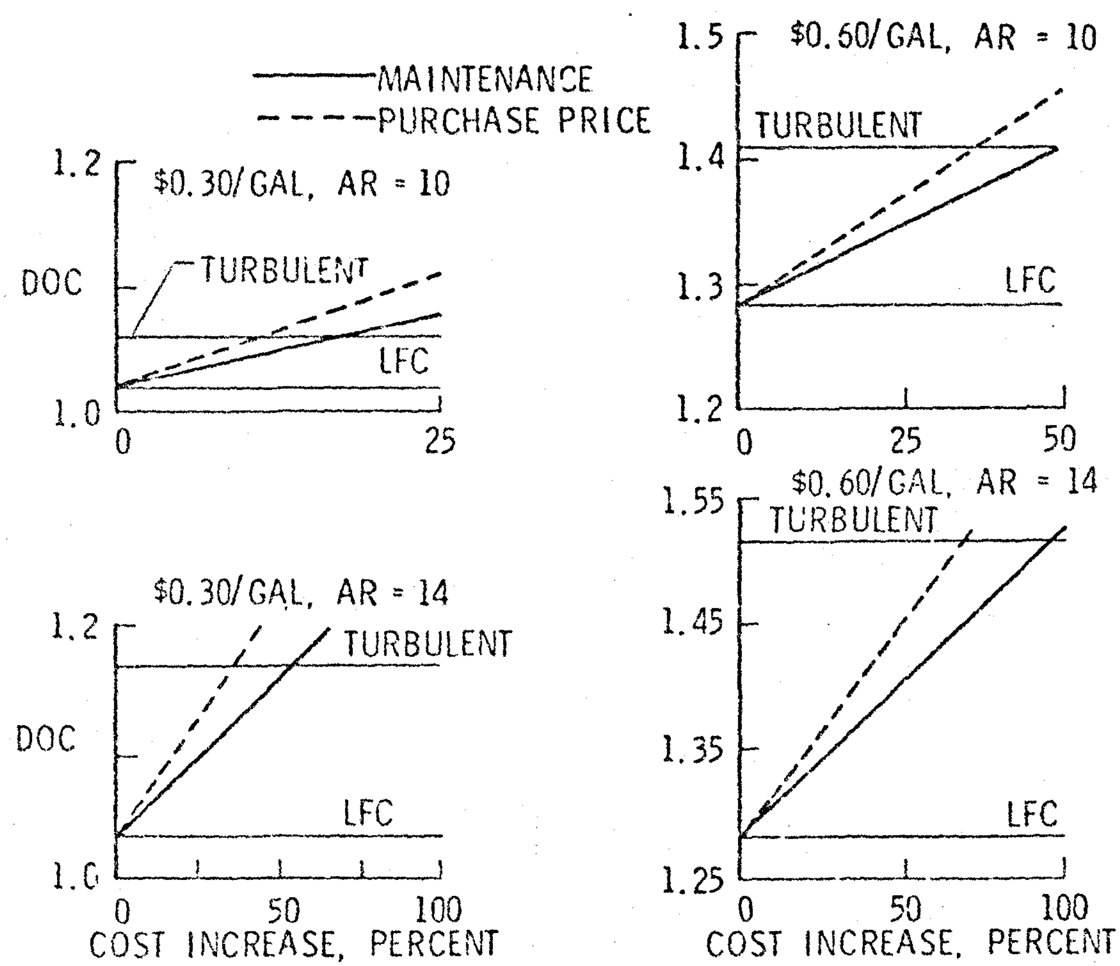

Figure 16. Effect of purchase price and maintenance cost increases on LFC economics at R = 3000 n.mi.